MAB-220-M

FINAL REPORT
of the
PANEL ON LUBRICATION
to the
AD HOC COMMITTEE ON
METALWORKING PROCESSES AND EQUIPMENT

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National Academy of Sciences—
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Prepared by the
Materials Advisory Board
Division of Engineering and Industrial Research
National Research Council

as a service of
The National Academy of Sciences
to the
Office of Defense Research and Engineering
Department of Defense

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INTRODUCTION

The Panel on Lubrication was activated in June, 1964, as an adjunct of the Materials Advisory Board Committee on Metalworking Processes and Equipment. The general objective of this Committee is to assist the Government Steering Group of the Metalworking Processes and Equipment Program and to serve as a coordinating and communications link between government, academic, and industrial interests. The Metalworking Processes and Equipment Program (MPEP) was initiated primarily as a result of recent advances in materials whose greater strength, hardness and heat resistance have engendered a need for improved fabrication technology and equipment.

The Committee has approached this task by selecting for review and study certain areas which appear to offer significant opportunity for process development. The findings and recommendations of the Committee are transmitted to the Government Steering Group on MPEP composed of representatives from each of the services through the medium of minutes and informative reports. These are used by the Government Steering Group as a guide in formulating projects and coordinating them in Government sponsored programs in metal deformation research and development.

In reviewing Government Sponsored research programs on metalworking, it was evident that very little effort was being expended in the area of metalworking lubricants. The Committee members felt this to be an important area for development and one that demanded a thorough review and

study. Because this was a subject area involving surface chemistry as well as metal deformation and mechanics, the Committee felt this review could be handled best by a Panel in which these disciplines were brought together.

Consequently, a Panel on Lubrication was established to survey the state of knowledge of friction and lubrication as they relate to deformation processes and equipment.

The present need for new metalworking lubricants arises out of the development of new structural materials created for the defense industry. Because these materials by their nature are more difficult to form, and because of the desire to obtain the lightest sections possible, the limits of present deformation processes are inadequate. Moreover, these new metals and alloys present different reactive surfaces to the lubricants, and many lubricants effective with traditional metals are ineffective with these new metals. A specific example is the fabrication of titanium.

The Panel chose to function by inviting persons active in the field of metalworking lubricant research to present their views on specific topics to stimulate discussion among the Panel members. It was intended that through these discussions the range of available knowledge

and its specific limits would be recognized. The topics selected followed a general sequence covering the available theory and technology of lubrication and the application of this theory and technology to metalworking processes. Speakers invited before the Committee included representatives of Government and independent research laboratories and representatives of producers and industrial users of metalworking lubricants. A list of the participants and the specific topics which they discussed are given in Appendix I.

DEFORMATION PROCESSING REQUIREMENTS

One of the most frequently stated purposes of a lubricant is to reduce friction, i.e., the force which is the resistance to sliding. The importance of this function, however, is often over-stated and varies according to the actual operation and objectives involved.

In metalworking operations the lubricant serves not only to reduce friction, but to minimize wear of the tools and control the surface finish of the workpiece. Although reduction of friction is generally considered as a measure of lubricant quality, the elimination of wear or metal transfer between tool and workpiece is usually the more stringent requirement. The specific requirements of a particular metalworking operation will dictate whether low wear or low friction is more important.

FRICTION:

In certain metalworking operations, friction can be an advantage as in a rolling operation where heavy reductions are being attempted and the angle of maximum acceptance decreases with decreasing friction. Normally, however, friction is considered a liability, as frictional forces augment the forces and power required to deform the metal. The effect of friction on force and power can usually be expressed in terms of some complex function of the coefficient of friction. Figure 1 shows a typical plot of the force required to forge a cylinder in plane strain compression as a function of the coefficient of friction and a geometrical parameter h/L,

where h and L express the effective height and length of deformation zone.

For values of h/L of one or more, friction is unimportant relative to other variables in the system such as the work-hardening capacity of the metal itself. On the other hand, as the sections being deformed become thinner and the parameter h/L decreases, friction plays an over-whelming role in establishing force and power requirements, and thus the limits of reduction. Although the advent in recent years of very powerful metal-working machinery has offset the significance of force and power as limiting factors, other limitations are imposed by frictional forces. For instance, the total force in an extrusion operation may exceed the strength of available die materials, or the torque transmitted through a roll neck may be limited by the strength of engineering materials. In other operations, where the force for deformation is supported by the workpiece itself, as in the case of wire drawing, the limiting reduction for a given die angle is fixed by the coefficient of friction.

Lastly, friction influences the pattern of bulk deformation of the workpiece and therefore the shape finally assumed by it. Excessive friction may make it impossible to produce complicated shapes by metal working, especially those comprising thin portions, e.g., finned tubes and thin turbine blades.

WEAR:

Most all products manufactured by plastic metalworking are expected to conform to certain surface standards. Wear is one of the most important factors affecting surface finish. However, the lubricant that would produce minimum wear and the lowest coefficient of friction usually is not the best to achieve a desired surface finish.

The term "optimum finish" does not necessarily have the same meaning for all applications. A relatively rough finish may be preferred in some cases, whereas a good finish in the common sense, meaning a bright surface, is desired in other cases. In the former, a very good lubricant with respect to friction might be desired, whereas in the latter a bright surface would normally be obtained by using a relatively poor lubricant. Thus, the requirements of surface finish and the desire of reduced friction may often be contradictory. In essence, the attainment of the desired surface finish is usually obtained through controlled wear with some sacrifice in coefficient of friction. This denotes wear of the workpiece itself. However, at the same time, metal pick-up on the tool surface must be prevented. Metal pick-up or galling, of the tool surface is usually an indication of lubricant failure. Usually the process is self accelerating.

Metal transfer is perhaps a more serious problem in terms of die wear. Wear of the work material, as long as the surface finisn is acceptable, is usually not a cause of undue concern. However, if the

properties of the die and workpiece material are such that the metal-metal junctions may be sheared in the bulk of the die, then accelerated die wear will be encountered. Severity of the problem depends on the type of operation performed. For instance, in very high temperature deformation of refractory metals, die wear can be a very serious problem as there are few materials which can withstand the high temperatures and severe pressures required.

OTHER CONSIDERATIONS:

The selection of a lubricant or lubrication system will depend on which of these requirements, i.e., low friction or low wear is more important. This depends on the specific forming conditions and objectives. If the objective is to obtain thin sections of difficult to form materials, where the limit of reduction of the processing equipment is being approached, then the demands of low friction are more important than surface finish or wear. Levels of friction consistent with good surface finish only may be too high.

On the other hand, where the limiting reduction of the process or equipment is not a factor, as in most commercial operations, then elimination of severe die wear and attainment of reasonable surface finish is a more practical goal. Such may be the case in the early stages of development of new materials, where ultimate fabrication limits are not yet important.

In addition to meeting these requirements a lubricant may also be employed in deformation processing to control the temperature of the workpiece or die. Other attributes may also be demanded of the lubricant according to the specific operation. These may include an ability to perform over a wide range of pressures, temperatures, sliding velocities, and metal surfaces, as well as freedom from discoloration or staining of the product, toxicity, odor, and fire hazard. Ease of application and removal are also important. It should also be inexpensive. Often a potential lubricant must be discarded because of its failing in these areas despite its ability to lower friction or decrease wear.

STATE OF KNOWLEDGE OF FRICTION, WEAR, AND LUBRICATION

FRICTION AND WEAR:

A physically satisfying explanation for the independence of frictional force from apparent area of contact, and the proportionality of friction force to load was first provided by the adhesion theory of friction developed about 1940. (1,2 and 3) According to this theory the major component of friction is due to the welding and shearing of asperities on the metal surfaces as they slide over one another. Few surfaces are truly flat. Most contain macro and microscopic undulations such that the real area of contact between two surfaces may only be 1/400th to 1/1,000,000th the apparent area of contact. Under the resultant high stresses and plastic deformation associated with sliding the asperities weld together. The total frictional force is then the product of the real area of contact and the average stress to shear the welding asperities. This yields for the coefficient of friction the equation:

$$f = \frac{s_m}{p_m} = \frac{\text{shear strength of metal}}{\text{yield pressure of metal}}$$

Although this equation nominally describes experimental data for many conditions, it implies that s_m and p_m are independent properties, which they are not. This equation holds only in the region of light loads where Amonton's Law (that real area of contact and friction force are directly proportional to load) holds. At the greater loads of interest to metalworking processes, the real area of contact approaches the apparent area

of contact and the friction force is dictated increasingly by the shear strength of the bulk material.

The result of the continual welding and shearing of asperities is both the transfer of metal from one piece to another and the generation of discrete loose particles where the sheared asperities are torn from both members, i.e., wear. The rate of wear is, like friction, a function of the real area of contact. It is, however, more complex in that it is also a function of where the asperities are sheared. Because of the work-hardening or oxide formation, shear may occur at a zone other than the interface. Thus, wear may be either mild or severe, depending on the zone of shear.

An expression was developed by Holm (2) and Archard (4) to describe wear phenomena, based on the occurrence of occasional metal-to-metal contact during sliding. This equation gives the "laws" of adhesive wear, namely, that wear is independent of the apparent area of contact and directly proportional to load. Thus,

$$W = \frac{KPS}{P_m}$$

where:

W - volume of metal removed

P - load

S - sliding distance

K - a constant, based on the probability of an asperity encountered removing metal

P_m - yield pressure of the softer metal

For the sliding of a given metal, the constant K expresses the effectiveness of lubrication and can be thought of as the coefficient of wear. While a useful expression to describe the generalized wear behavior, it is one of little value in explaining differences in rates of wear of different metals of similar hardness.

UNLUBRICATED METALS:

There are considerable differences in friction and wear behavior between some metal combinations and others. For dry unlubricated metals, friction and the size and number of wear particles are influenced by the "similarity" as well as the hardness of the surfaces in contact. Where surfaces are alike,wear is more likely to be severe and friction higher, than when surfaces are unlike.

Several modifications of the adhesion theory of friction and wear have been proposed to account for these differences between metals. Most are based on some measure of "similarity" of the metals, such as position in the periodic table, mutual solubility, or surface energy of adhesion. The recent theory of Rabinowicz (5) is characteristic of this approach.

According to this theory, the interaction (and thus friction and wear) is proportional to the ratio of the surface energy to adhesion, Wab, to the yield pressure of the metal P_m. This theory incorporates the concept of similarity in the value of Wab. This approach leads to an expression for friction:

$$f = \frac{s_m}{p_m} \left[1 + \frac{2\,Wab \cot \theta}{p_m r} + \ldots \right]$$

where:

θ and r relate to junction geometry.

Similar equations can also be developed to relate size of the wear particle to Wab/P_m. This theory, however, still appears to be in a stage of development, and present experimental results indicate only a qualitative relationship at best. To date there is little or no basis for quantitative prediction of friction or wear of unlubricated metals under different sliding conditions. One of the difficulties in applying the above equation is to obtain accurate values for the surface energy of adhesion, Wab.

LUBRICATED METALS:

The basis of lubrication is either to separate the metal surfaces so they are no longer in contact or to change the surface chemistry or hardness so as to reduce friction and wear.

In principle, there are two kinds of lubrication, thick film lubrication and thin film or "boundary" lubrication. In practice, it may frequently be a mixture of the two. In thick film lubrication, the lubricant is present in the form of continuous film which is so thick as to keep apart all asperities of the two surfaces in nominal contact. The real area of contact is reduced to zero, and the coefficient of friction, roughly between 0.001 and 0.01, depends on dynamic viscosity or shear strength

of the lubricant itself. Although thick film lubrication is most often based on liquid films, lubricants of solids and gases may function in a similar manner.

In boundary lubrication, the lubricant film is usually of molecular dimensions and not necessarily continuous. However, even if the lubricant film is continuous, asperities of the two surfaces are in effective contact and the coefficient of friction is a function both of the properties of the lubricant and the properties of the surfaces and their interaction with the lubricant. Essentially the real area of contact remains about the same; the lubricant therefore functions presumably by reducing the stress required to shear the welded asperities and/or by modifying the zone of shear. Generally, the coefficient of friction is the range of 0.01 to 0.20.

Under conditions of thick film lubrication there is no wear. Under conditions of boundary lubrication, wear can be a far more sensitive measure of the effectiveness of a lubricant than friction itself.

Boundary Lubrication

No completely satisfactory quantitative treatment of boundary lubrication has been established. Several theories exist; among these the solid film theory of Tabor (6) is typical. This theory is based on the presence of a solid film or one or both of the surfaces which is adherent and sufficiently tough to resist rupture. This film may be a monolayer

of physically absorbed material, a chemisorbed material, or a chemical reaction film such as an oxide or inorganic salt.

The solid film theory of boundary lubrication is essentially an extension of the adhesion theory of friction to account for the tendency of the real area of contact to increase with tangential force, and the effect of surface films in limiting junction growth of the asperities.

This yields the equation:

$$f = \frac{s_i}{p_m} = \frac{1}{3\,(k^{-2}\ -1)^{\frac{1}{2}}}, \quad k = \frac{s_i}{s_m}$$

where:

s_i - the shear strength of the film

p_m - the yield pressure of the metal

s_m - the shear strength of the metal

k - the ratio of shear strength of the film to that of the metal

A plot of $\frac{s_i}{p_m}$ versus k is shown in Figure 2. As k approaches 1, that is, when the shear strength of the film s_i approaches the shear strength of the metal s_m, friction is high > 2. This condition corresponds to very clean metals. However, as soon as s_i is 5 percent less than s_m, $k = 0.95$, friction falls to unity. Thus, a very small weakening of the surfaces reduces friction drastically. This condition might correspond to an oxide film on a steel surface. A film with a shear stress one-tenth of the metal would reduce friction to 0.03. This corresponds to a film of soap on a metal surface.

The analysis suggests that an investigator could predict coefficient of friction, given sufficient information with regard to film formation and strength, and thus choose a film to give desired optimum friction. A present limitation of the theory is that the shear strength and other properties of films are not known at the temperature and pressures of the sliding interface. Thus, there has been little opportunity to verify the theory or apply it quantitatively.

Among other theories of boundary lubrication, that of Rebinder (7), popular among Soviet investigators, has received probably the greatest attention. This theory proposes that adsorbed films accelerate the deformation of solids and reduce their strength and hardness. The effect is most evident in single crystals and specimens of small dimensic s where surfaces play a predominant role. The theory has not received wide acceptance outside the Soviet Union and even there, is considered somewhat controversial.

At present there does not seem to be any fundamen al theory to explain differences of wear of metals under conditions of mdary lubrication. However, the "law of wear" as expressed by the Archard equation (4) has been used to predict differences in wear based on laboratory tests. This appears to be a very complex subject, still dependent largely on an empirical approach.

Thick Film Lubrication

This regime of lubrication is governed by the bulk properties of the lubricant. In most common applications the physical properties and microgeometrical details of the two mating surfaces can be entirely disregarded, and, in the case of liquid films, the problem treated as one of fluid flow through a smooth converging duct of rigid dimension acted upon by a simple system of external forces.

The theory of hydrodynamic lubrication is highly developed. While most solutions have dealt with steady state problems, and Newtonian viscosity, some non-steady state solutions have been attempted. Generally, the theory of hydrodynamic thick film lubrication has been developed to such a degree that in principle any problem in the field of metalworking could be tackled, subject only to the degree of complexity of the ensuing equations. The theory is backed by and correlates satisfactorily with voluminous experimental data. Mention should also be made of hydrostatic lubrication in which the load bearing capacity of the lubricant film is provided by an external high pressure source of lubricant; in lieu of the forces generated internally by the action of the high speed relative motion of the mating surfaces.

Thick film lubrication is not, however, limited to liquid films. Films of gases and solids are also used as lubricants. In the case of gas films the theory of compressible fluids applies, and thus, is more

complex than that of hydrodynamic theory. For this reason solutions of gas film lubrication are generally limited to relatively simple geometrics. Because of the relatively light loads that can be supported by gas films, gas lubrication is not generally applicable to metalworking.

Solid film lubrication on the other hand is of great interest in metalworking and can be adequately described by the following equation:

$$f = \frac{s_i}{P_m}$$

where:

s_i - is the shear strength of the solid film

P_m - is the yield pressure of the substrate and film combination

It is interesting to note that as the film thickness increases beyond a certain point, the value of P_m decreases due to the increasing influence of the film itself and thus, the friction increases with increasing film thickness. This is analogous to hydrodynamic thick film lubrication. While little experimental work has been carried out to validate this theory for a wide range of conditions, the data available does correlate reasonably well with theory.

Mixed Lubrication

While one can define regions of boundary lubrication and thick film lubrication, in metalworking practice, one generally encounters a combination of both. Thus, in the case of hydrodynamic lubrication, there is

increasing opportunity for boundary lubrication at asperities as the film diminishes in thickness.

A direct approach to this problem has recently been examined, in which thick film hydrodynamic theory is taken as a starting point and modified by stages in which additional factors significant in thin films are introduced. This approach has stimulated recently a good deal of theoretical and experimental research on what has come to be known as "elasto-hydrodynamic" lubrication. At present, however, there is still much scope for further development of both theory and experiment.

APPLICATION OF KNOWLEDGE TO DEFORMATION PROCESSING

Except for hydrodynamic lubrication, present theories of lubrication, friction and wear have not received broad application. This may be due in part to the inability of these theories to properly identify all contributing influences. More likely, however, it is because they depend on properties (such as Wab or s_i) which in themselves are more difficult to measure than either the coefficient of friction or coefficient of wear. For this reason much of the practical art of lubrication is based on the results of simple sliding tests and experience rather than on theory. In metalworking, particularly, the selection of lubricants has been one of trial and error. Little cognizance is taken of available theories and principles; only full-scale tests are considered reliable.

Perhaps the principal barrier to the application of existing lubrication knowledge to metalworking is that it is based to a large extent on sliding conditions much different than those in metalworking. Almost all basic and applied research in the lubrication field has been concerned with elastic bodies. Few studies have been carried out at pressures and temperatures and with metal pairs relevant to metalworking. Consequently, the theories based on these studies and, more importantly, most of the empirical data on friction and wear presently available are not directly applicable to deformation processing.

On the other hand, metalworking experts have not availed themselves of some of the techniques used in the lubrication field for evaluating lubricants. While many of the existing data and theories may not be applicable to metalworking, the principles and techniques developed should be equally useful in the metalworking field. Specific techniques or principles which might be applied are:

(1) The use of pin-slider tests for preliminary screening of lubricants and fundamental studies of friction and wear under metalworking conditions.

(2) The microscopic observation of the sliding surfaces of the metal and die to determine the nature of friction and wear, as an aid in the selection of lubricants.

(3) The selection of tool materials based on their relative interaction with the workpiece where unlubricated conditions may prevail.

(4) The design of tools to promote hydrodynamic lubrication,where extremely low friction or low wear is required.

To the extent available knowledge is not being used, progress in this field is handicapped.

CONCLUSIONS AND RECOMMENDATIONS

The Panel's discussion and deliberations have lead to the following conclusions:

(a) There is a lack of adequate communication between specialists in the lubrication field and specialists in the metal deformation field.

(b) Little of the available basic knowledge of friction, wear, and lubrication is being used to extend metal deformation processing limits.

(c) Although a number of bench tests are currently used to empirically evaluate lubricants, little is known of the extent of their applicability to industrial metalworking operations.

(d) There is little data on the physical properties of surfaces and surface films, such as shear strength of oxides, under conditions of pressure and temperature germane to metalworking.

Based on these conclusions, the following recommendations are made:

RECOMMENDATION (1)

The Panel's discussions have more than other things highlighted the lack of adequate communication between lubrication and metalworking specialists. Specialists in the two fields have little awareness of the others know-how. It would appear that a book or monograph which would bring together up-to-date developments in these two fields as they relate to each other would be desirable.

Specifically an individual or group should be commissioned to prepare a monograph on metalworking lubrication. In addition to bringing together the up-to-date developments in lubrication and metalworking, it should also deal with the following issue.

Since metalworking lubrication serves both the functions of controlling wear and decreasing friction, the understanding of which varies and which are not always compatible, the practice is dominated by empiricism. It is then important to be sure that there is at least a clear understanding of the difference in functions and the scientific knowledge relevant to each so that any trial and error approach is properly

guided by the knowledge available.

RECOMMENDATION (2)

Thick film lubrication represents the most advanced state of the art of lubrication. Moreover, minimum friction and minimum wear are obtained under thick film lubrication conditions. Successful exploitation of thick film lubrication in metalworking operations should yield rewards. In only one process (wire drawing) has there been an effort to bring this condition about deliberately and control it. The possibility exists of extending this approach to other deformation processes.

Specifically, carry out analysis and experimental studies on a selected deformation process, e.g., tube drawing or extrusion, with the aim of promoting thick film lubrication through die design as well as lubricant selection. Theoretical analysis, evaluation of rheological properties of lubricants under prevailing sliding conditions, and full scale trials should be considered in the program.

RECOMMENDATION (3)

In selecting and studying boundary lubricants for bearing and related applications, simple screening tests, such as the pin slider test have proven effective. The test as presently used involves sliding of bodies which are loaded elastically. There are differences of opinions regarding the application of such tests to metalworking operations involving a plastically deforming body. Present theory and experience is

not sufficiently broad to answer this question.

As pin slider tests are fairly common, and yet easily modified to study a wide range of variables, they represent a potential asset to the development of metalworking lubricants if their results are relatable to metalworking conditions. It would be desirable to determine whether pin slider tests are valid for metalworking and adapt or modify the tests as required. In particular, ascertain how far results of pin slider tests are affected by bulk plastic deformation of the specimen and generation of new surface.

Specifically, pin-slider tests should be carried out with several tool workpiece combinations under unlubricated and lubricated conditions. Load, sliding velocity and temperature should be varied over the range these variables experience in an actual metalworking operation. Observation and measurements should be made of metal transfer, wear, friction, and metal-to-metal contact on both pin slider tests and in simple metalworking operations selected for comparison to emphasize changing surface area. Wire drawing or sheet forming would be considered ideal operations for comparison with test results.

RECOMMENDATION (4)

One class of lubricants used widely in metalworking are solid lubricants including preformed films of soft metals, organic polymers, greases, soaps, fats and waxes, oxide coatings, inorganic conversion

coatings and laminar solids. Theoretically the efficiency of these lubricants depends on their shear strength but little is known about their relative strengths under conditions of high pressures, temperatures and shear rates.

Specifically, measure the shear strength and observe the behavior of potential solid lubricants during sliding at high pressures, temperatures, and shear rates. Use these three data to test theories of friction as they may apply to metalworking. This would be a continuation and expansion of P. W. Bridgman's work (9).

RECOMMENDATION (3)

Research should be sponsored in the general area of compatibility or similarity of contacting metals with special emphasis on metal pairs of interest in metalworking operations. The results would be directly applicable to the problem of choosing the best tool material to be used in operations with marginal lubrication possibilities.

Specifically, testing should be carried out on unlubricated surfaces, and measurements of friction, wear, metal transfer and surface finish should be made. It will be the purpose of the proposed study to find the theory which is most applicable to tool materials.

In order of priority the Panel considers recommendations (1), (2), and (3) of primary importance and more likely to yield returns in

the near future and recommendations (4) and (5) of secondary importance and longer range in scope.

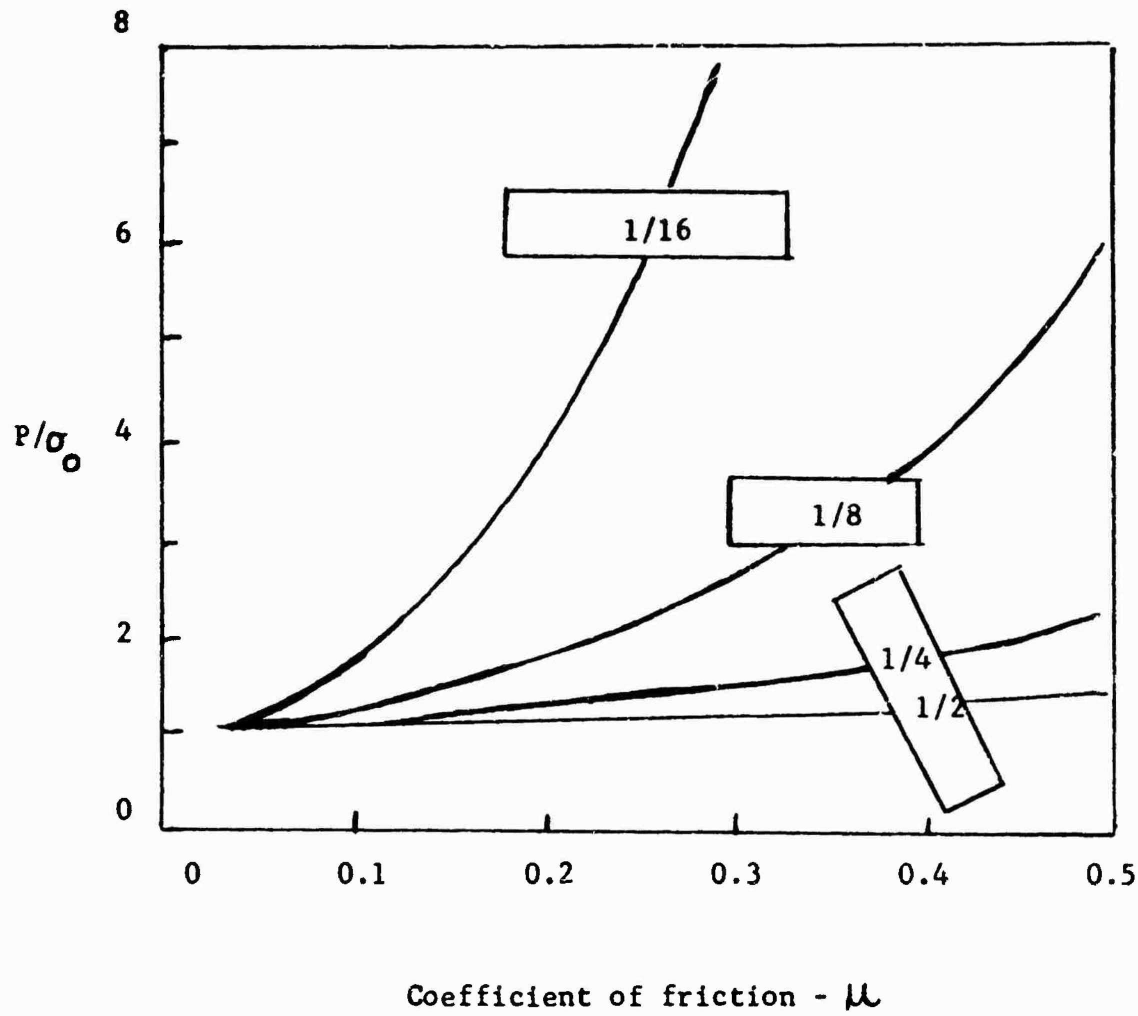
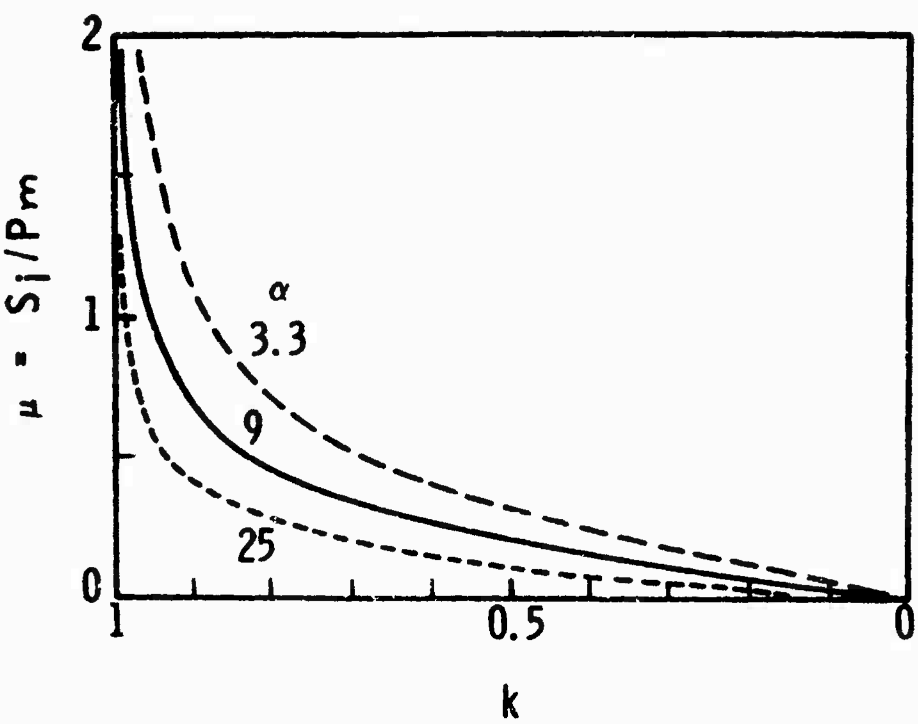


FIGURE 1. - Force for forging cylinder in plane strain as a function of deformation zone geometry and friction. Lines correspond to different h/L values where h and L are the height and length of the deformation zone. P/σ_o is the ratio of forging pressure to flow strength of the material.

FIGURE 2



Coefficient of friction, μ, as a function of $K = s_i / s_m$.

The above curves are for $\alpha = 3.3$, $\alpha = 9$ and $\alpha = 25$.

α is a constant in the relation $\mu = \dfrac{}{\sqrt{\alpha}\,(K^2 - 1)^{\frac{1}{2}}}$

From Tabor, Reference 6.

APPENDIX I

LIST OF OUTSIDE PARTICIPANTS WHO MADE PRESENTATIONS TO THE PANEL

First Meeting:	Dr. John A. Schey IIT Research Institute June 17, 1964 "Purposes and Attributes of Metalworking Lubricants"
Second Meeting:	None
Third Meeting	Dr. R. L. Adamczak, Chief Fluid and Lubricant Materials Branch Air Force Materials Laboratory Wright-Patterson Air Force Base December 9, 1964 "Fluid and Lubricant Materials Research"
	Mr. Frank Lake Thompson-Ramo-Wooldridge, Inc. "High Temperature Extrusion Lubricants"
	Dr. J. C. Bell Battelle Memorial Institute "Investigation of the Process of Lubrication of Rolling Contact"
Fourth Meeting	Dr. W. L. Roberts U. S. Steel Corporation Applied Research Laboratories March 17, 1965 "The State of Development of Lubricants for Cold Rolling Applications"
	Dr. W. J. Wojtowicz H. A. Montgomery Company "The Selection of Lubricants for Sheet Metalworking Applications"

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13. ABSTRACT

In 1963, the Assistant Director (Materials) of the office of Director Defense Research and engineering, Department of Defense, requested the National Academy of Sciences-National Research Council to provide advice and guidance to the Steering Group of the Government's Metalworking Processes and Equipment Program. The Government Metalworking Processes and Equipment Program is a coordinated effort of the Army, Navy, Air Force and NASA to identify salient factors which limit metal deformation processes and concurrently to sponsor research to extend these limits for improvement of manufacturing capabilities. Accordingly, the Materials Advisory Board Committee on Metalworking Processes and Equipment has been organized to provide technical guidance to the program.

The Panel on Lubrication of the Committee on Metalworking Processes and Equipment has surveyed the state of knowledge of friction and lubrication as they relate to deformation processes and equipment. This report summarizes the findings and presents five recommendations.

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